

50103-426/STL 3067

HEAT-TRANSFER-STAMP PROCESS
FOR THERMAL IMPRINT
LITHOGRAPHY

CROSS-REFERENCE TO PROVISIONAL APPLICATION

This application claims priority from U.S. provisional patent application Serial No. 60/312,928 filed August 16, 2001, the entire disclosure of which is incorporated herein by reference.

5 FIELD OF THE INVENTION

The present invention relates to methods and devices for forming sub-micron sized features and patterns in large area substrate surfaces by means of thermal imprint lithography. The invention has particular utility in the formation of servo patterns in the surfaces of substrates utilized in the manufacture of data/information storage and retrieval media, e.g., hard disk magnetic media.

BACKGROUND OF THE INVENTION

Optical-based lithographic techniques are widely employed in the fabrication of integrated circuits (ICs) and other devices requiring very fine-dimensional patterns or features. However, the constantly increasing demands of micro-miniaturization for increased data storage and computation require fabrication of devices with ever smaller dimensions, which demands tax or even exceed the limits of conventional optical lithographic patterning processes utilizing visible light. As a consequence, intense research has been conducted on ultra-violet (UV), X-ray, electron beam (e-beam), and scanning probe (SP) lithography. However, while each of these techniques is capable of providing high resolution, finely-dimensioned patterns and features, the economics of their use is less favorable, due to such factors as limitations

arising from wavelength- dependent phenomena, slow e-beam and SP writing speeds, and difficulties in the development of suitable resist materials.

Thermal imprint lithography has been recently studied and developed as a low cost alternative technique for fine dimension pattern/feature
 5 formation in the surface of a substrate or workpiece, as for example, described in U.S. Pats. 4,731,155; 5,772,905; 5,817,242; 6,117,344; 6,165,911; 6,168,845 B1; 6,190,929 B1; and 6,228,294 B1, the disclosures of which are incorporated herein by reference. A typical thermal imprint lithographic process for forming nano-dimensioned patterns/features in a substrate surface
 10 is illustrated with reference to the schematic, cross-sectional views of FIGS. 1(A) - 1(D).

Referring to FIG. 1(A), shown therein is a mold **10** (also termed a "stamper/imprinter") including a main body **12** having upper and lower opposed surfaces, with a molding (i.e., stamping/imprinting) layer **14** formed
 15 on the lower opposed surface. As illustrated, molding layer **14** includes a plurality of features **16** having a desired shape or surface contour. A workpiece comprised of a substrate **18** carrying a thin film layer **20** on an upper surface thereof is positioned below, and in facing relation to the molding layer **14**. Thin film layer **20** is typically comprised of a thermoplastic
 20 material, e.g., polymethyl methacrylate (PMMA), and may be formed on the substrate/workpiece surface by any appropriate technique, e.g., spin coating.

Adverting to FIG. 1(B), shown therein is a compressive molding step, wherein mold **10** is pressed into the thin film layer **20** in the direction shown by arrow **22**, so as to form depressed, i.e., compressed, regions **24**. In the
 25 illustrated embodiment, features **16** of the molding layer **14** are not pressed all of the way into the thin film layer **20** and thus do not contact the surface of the underlying substrate **18**. However, the top surface portions **24a** of thin film **20** may contact depressed surface portions **16a** of molding layer **14**. As a consequence, the top surface portions **24a** substantially conform to the shape
 30 of the depressed surface portions **16a**, for example, flat. When contact between the depressed surface portions **16a** of molding layer **14** and thin film layer **20** occurs, further movement of the molding layer **14** into the thin film

layer 20 stops, due to the sudden increase in contact area, leading to a decrease in compressive pressure when the compressive force is constant.

FIG. 1(C) shows the cross-sectional surface contour of the thin film layer 20 following removal of mold 10. The molded, or imprinted, thin film layer 20 includes a plurality of recesses formed at compressed regions 24 which generally conform to the shape or surface contour of features 16 of the molding layer 14. Referring to FIG. 1(D), in a next step, the surface-molded workpiece is subjected to processing to remove the compressed portions 24 of thin film 20 to selectively expose portions 28 of the underlying substrate 18 separated by raised features 26. Selective removal of the compressed portions 24, as well as subsequent selective removal of part of the thickness of substrate 18 at the exposed portions 28 thereof, may be accomplished by any appropriate process, e.g., reactive ion etching (RIE) or wet chemical etching.

The above-described imprint lithographic processing is capable of providing submicron-dimensioned features, as by utilizing a mold 10 provided with patterned features 16 comprising pillars, holes, trenches, etc., by means of e-beam lithography, RIE, or other appropriate patterning method. Typical depths of features 16 range from about 5 to about 500 nm, depending upon the desired lateral dimension. The material of the molding layer 14 is typically selected to be hard relative to the thin film layer 20, the latter typically comprising a thermoplastic material which is softened when heated. Thus, suitable materials for use as the molding layer 14 include metals, dielectrics, semiconductors, ceramics, and composite materials. Suitable materials for use as thin film layer 20 include thermoplastic polymers which can be heated to above their glass temperature, T_g , such that the material exhibits low viscosity and enhanced flow.

Referring now to FIG. 2, schematically illustrated therein, in simplified cross-sectional view, is a typical sequence of processing steps for performing nano-imprint lithography of a metal-based substrate/workpiece, i.e., an Al/NiP substrate/workpiece, utilizing a conventional "master" or stamper/imprinter, e.g., a Ni-based stamper/imprinter. In a preliminary step, a thin film of a thermoplastic polymer, i.e., polymethyl methacrylate (PMMA) is spin-coated

on an annular disk-shaped Al/NiP substrate/workpiece, corresponding to substrates conventionally employed in the manufacture of hard disk magnetic recording media. In another preliminary step, a Ni stamper/imprinter having an imprinting surface with a negative image pattern of features, e.g., a servo pattern with lateral dimensions of about 600 nm and heights of about 170 nm, is fabricated by conventional optical lithographic patterning/etching techniques, provided with a thin layer of an anti-sticking or release agent (typically a fluorinated polyether compound such as ZdolTM, available from Ausimont, Thorofare, NJ), and installed in a stamping/imprinting tool. In the next step according to the conventional methodology for performing thermal imprint lithography, the substrate/workpiece is placed in the stamping/imprinting tool and heated along with the stamper/imprinter to a temperature above the glass transition temperature (T_g) of the PMMA, i.e., above about 105°C, e.g., about 120°C, after which the patterned imprinting surface of the Ni-based stamper/imprinter is pressed into contact with the surface of the heated thermoplastic PMMA layer on the substrate/workpiece at a suitable pressure, e.g., about 10 MPa. As a consequence, the negative image of the desired pattern on the imprinting surface of the Ni-based stamper/imprinter embossed into the surface of the thermoplastic PMMA layer. The stamper/imprinter is then maintained within the stamping/imprinting tool in contact with the PMMA layer and under pressure for an interval until the system cools down to an appropriate temperature, e.g., about 70°C, after which interval the substrate/workpiece is removed from the stamping/imprinting tool and the stamper/imprinter separated from the substrate/workpiece to leave replicated features of the imprinting surface in the surface of the PMMA layer.

A significant drawback associated with the above-described thermal imprint lithography process is the extremely long interval, e.g., 15 - 25 min., required for thermal cycling of the relatively massive stamping/imprinting tool utilized for imprinting each workpiece or group of workpieces (e.g., typically involving heating of the tool to about 200°C for imprinting of the substrate/workpiece, followed by cooling to about 70°C for removal of the

imprinted substrate/workpiece from the tool). Such long thermal cycling intervals are incompatible with the product throughput requirements for large-scale, economically competitive, automated manufacturing processing of e.g., hard disk magnetic recording media.

- 5 In view of the above, there exists a need for improved methodology for performing thermal imprint lithography which eliminates, or at least substantially reduces, the disadvantageously long interval required for thermal cycling of the stamping/imprinting tool associated with conventional thermal imprint lithography. More specifically, there exists a need for improved
10 methodology for rapidly and cost-effectively imprinting or embossing a pattern, e.g., a servo pattern, in a surface of a resist or other type relatively soft layer on the surface of a substrate for a data/information storage and retrieval medium, e.g., a hard disk magnetic recording medium.

- The present invention addresses and solves drawbacks associated with
15 long thermal cycling intervals associated with conventional techniques and methodologies for performing thermal imprint lithography for pattern definition in substrate/workpiece surfaces, such as in the fabrication of hard disk substrates with integrally formed servo patterns, while maintaining full compatibility with all aspects of conventional automated manufacturing
20 technology for pattern formation by imprint lithography. Further, the methodology and means afforded by the present invention enjoy diverse utility in the imprint lithographic patterning of a variety of substrates and workpieces.

DISCLOSURE OF THE INVENTION

- 25 An advantage of the present invention is an improved method of performing thermal imprint lithography of a workpiece surface, whereby the disadvantageously long interval for thermal cycling of the stamping/imprinting tool is eliminated, or at least substantially reduced.

- Another advantage of the present invention is an improved method of
30 performing thermal imprint lithography for patterning of substrates utilized in the manufacture of hard disk recording media.

Still another advantage of the present invention is an improved method of performing thermal imprint lithography for forming servo patterns in substrates utilized in the manufacture of hard disk recording media.

Additional advantages and other aspects and features of the present invention will be set forth in the description which follows and in part will become apparent to those having ordinary skill in the art upon examination of the following or may be learned from the practice of the present invention. The advantages of the present invention may be realized and obtained as particularly pointed out in the appended claims.

According to an aspect of the present invention, the foregoing and other advantages are obtained in part by a method of performing thermal imprint lithography of a surface of a workpiece for forming a pattern therein, comprising pre-heating the workpiece to a pre-selected elevated temperature prior to inserting the workpiece in a stamping/imprinting tool for performing the thermal imprint lithography, whereby the interval for thermal cycling of the stamping/imprinting tool between higher and lower temperatures is eliminated or at least reduced.

According to embodiments of the present invention, the temperature of the stamping/imprinting tool is maintained substantially constant at a pre-selected temperature lower than the pre-selected elevated temperature of the pre-heated workpiece.

In accordance with certain embodiments of the present invention, the method comprises the steps of:

- (a) providing a stamping/imprinting tool including a stamper/imprinter having an imprinting surface comprising a negative image of the pattern to be formed in the workpiece surface;
- (b) maintaining the stamper/imprinter of the stamping/imprinting tool at a pre-selected first high temperature;
- (c) providing a workpiece having first, upper and second, lower surfaces;
- (d) heating the workpiece to a pre-selected second high temperature greater than the pre-selected first high temperature;

- (e) transferring the heated workpiece to the stamping/imprinting tool;
- (f) urging the first, upper surface of the heated workpiece against the imprinting surface of the heated stamper/imprinter at a pre-selected high pressure sufficient to imprint the pattern in the first, upper surface;
- (g) continuing urging the first, upper surface of the heated workpiece against the imprinting surface of the heated stamper/imprinter at the pre-selected high pressure for a pre-selected interval, during which interval the temperature of the heated workpiece is lowered to the pre-selected first high temperature of the stamper/imprinter;
- (h) separating the imprinted surface of the workpiece from the imprinting surface of the stamper/imprinter; and
- (i) removing the workpiece from the stamping/imprinting tool.

According to particular embodiments of the present invention, step (c) comprises providing a workpiece in the form of a flat, disk-shaped substrate for a hard disk recording medium, the first, upper surface of the substrate being coated with a layer of a thermoplastic material, the substrate comprises Al, an Al-based alloy, NiP-coated Al, glass, ceramic, or a glass-ceramic composite material; step (a) comprises providing a stamping/imprinting tool including a stamper/imprinter having an imprinting surface comprising a negative image of a servo pattern to be formed in the first, upper surface of the workpiece, the stamper/imprinter having a Ni imprinting surface, the latter being coated with a layer of a release agent, e.g., a layer of a fluorinated polyether compound; step (b) comprises maintaining the stamper/imprinter at a pre-selected first high temperature close to a glass transition temperature T_g of the layer of thermoplastic material on the first, upper surface of the substrate; step (d) comprises heating the workpiece to the pre-selected second high temperature which is greater than the pre-selected first high temperature of the stamper/imprinter and greater than the glass transition temperature T_g of the layer of thermoplastic material on the first, upper surface of the substrate; and step (f) comprises commencing urging of the heated substrate against the imprinting surface of the heated stamper/imprinter when the temperature of

the heated substrate is above the glass transition temperature T_g of the layer of thermoplastic material on the first, upper surface of the substrate.

According to embodiments of the present invention, step (c) comprises providing a substrate including a first, upper surface coated with a layer of polymethyl methacrylate (PMMA) thermoplastic material having a glass transition temperature of about 105 °C; step (b) comprises maintaining the stamper/imprinter at a pre-selected first high temperature of about 120 °C; and step (d) comprises heating the workpiece to a pre-selected second high temperature of about 200 °C.

In accordance with further embodiments of the present invention, step (a) comprises providing a stamping/imprinting tool including first, upper and second, lower mounting means for respectively mounting thereon the stamper/imprinter and the workpiece, each of the first and second mounting means including heating means for maintaining the respective mounting means at the pre-selected first temperature; and step (e) comprises placing the second, upper surface of the heated workpiece in overlying relation to the second, lower mounting means.

According to still further embodiments of the present invention, step (c) comprises providing a workpiece having a thermally insulating spacer, e.g., of glass, in contact with the second, lower surface thereof, whereby the rate of temperature reduction of the heated workpiece from the pre-selected second, higher temperature established in step (d) is lowered relative to the rate of temperature reduction obtained in the absence of the thermally insulating spacer.

Another aspect of the present invention is a method of forming a desired pattern in a surface of a substrate for a hard disk recording medium, comprising the steps of:

(a) providing a substrate in the form of a flat disk having first, upper and second, lower surfaces, the first, upper surface being coated with a layer of a thermoplastic material;

(b) providing a stamping/imprinting tool including a stamper/imprinter having an imprinting surface comprising a negative image of the pattern to be formed in the surface of the substrate;

(c) maintaining the stamper/imprinter of the stamping/imprinting tool at a pre-selected first high temperature close to a glass transition temperature T_g of the layer of thermoplastic material on the first, upper surface of the substrate;

(d) heating the substrate to a pre-selected second high temperature which is greater than the pre-selected first high temperature of the stamper/imprinter and greater than the glass transition temperature T_g of the layer of thermoplastic material on the first, upper surface of the substrate;

(e) transferring the heated substrate to the stamping/imprinting tool;

(f) urging the heated substrate against the imprinting surface of the heated stamper/imprinter at a pre-selected high pressure sufficient to imprint the pattern in the layer of thermoplastic material on the first, upper surface of the substrate, wherein the temperature of the substrate when the urging of the heated substrate against the imprinting surface of the heated stamper/imprinter commences is above the glass transition temperature T_g of the layer of thermoplastic material on the first, upper surface of the substrate;

(g) continuing urging the heated substrate against the imprinting surface of the heated stamper/imprinter at the pre-selected high pressure for a pre-selected interval, during which interval the temperature of the heated substrate is lowered to the pre-selected first high temperature of the stamper/imprinter;

(h) separating the substrate with the imprinted layer of thermoplastic material thereon from the imprinting surface of the stamper/imprinter; and

(i) removing the substrate from the stamping/imprinting tool.

According to certain embodiments of the present invention, step (b) comprises providing the stamping/imprinting tool as including first, upper and second, lower mounting means for respectively mounting thereon the

stamper/imprinter and the substrate, each of the first and second mounting means including heating means for maintaining the respective mounting means at the pre-selected first temperature; and step (e) comprises placing the second, upper surface of the heated substrate in overlying relation to the

5 second, lower mounting means.

In accordance with further embodiments of the present invention, step (a) comprises providing a substrate having a thermally insulating spacer in contact with the second, lower surface thereof, whereby the rate of temperature reduction of the heated substrate from the pre-selected second,

10 higher temperature established in step (d) is lowered relative to the rate of temperature reduction obtained in the absence of the thermally insulating spacer.

According to particular embodiments of the present invention, step (a) comprises providing a substrate comprising Al, an Al-based alloy, NiP-coated

15 Al, glass, ceramic, or a glass-ceramic composite material, the substrate comprising a first, upper surface coated with a layer of a polymethyl methacrylate (PMMA) thermoplastic material having a glass transition temperature of about 105 °C; step (b) comprises providing a stamping/imprinting tool comprising a stamper/imprinter having an imprinting

20 surface including a negative image of a servo pattern to be formed in the thermoplastic PMMA layer on the first, upper surface of the substrate; step (c) comprises maintaining the stamper/imprinter at a pre-selected first high temperature of about 120 °C; and step (d) comprises heating the workpiece to a pre-selected second high temperature of about 200 °C; wherein step (b)

25 further comprises providing a stamper/imprinter having a Ni imprinting surface, the Ni imprinting surface including thereon a layer of a release agent.

In accordance with embodiments of the present invention, the method comprises the further steps of:

(j) forming the desired pattern in the first, upper surface of the

30 substrate by a process comprising selective removal of substrate material, utilizing the imprinted layer of thermoplastic material as a pattern-defining mask; and

(k) selectively removing the imprinted layer of thermoplastic material subsequent to performing step (j).

Additional advantages and aspects of the present invention will become readily apparent to those skilled in the art from the following detailed description, wherein embodiments of the present invention are shown and described, simply by way of illustration of the best mode contemplated for practicing the present invention. As will be described, the present invention is capable of other and different embodiments, and its several details are susceptible of modification in various obvious respects. Accordingly, the drawings and description are to be regarded as illustrative in nature, and not as limitative.

BRIEF DESCRIPTION OF THE DRAWINGS

The following detailed description of the embodiments of the present invention can best be understood when read in conjunction with the following drawings, in which the features are not necessarily drawn to scale but rather are drawn as to best illustrate the pertinent features, wherein:

FIGS. 1(A) - 1(D) are schematic, simplified cross-sectional views illustrating a process sequence for performing thermal imprint lithography of a thin resist film on a substrate (workpiece) according to the conventional art;

FIG. 2 schematically illustrates, in simplified cross-sectional view, another sequence of steps for performing imprint lithography of a resist film according to the conventional art;

FIG. 3 schematically illustrates, in simplified cross-sectional view, a sequence of steps for performing imprint lithography of a resist film according to an embodiment of the present invention;

FIG. 4 schematically illustrates, in simplified cross-sectional view, a sequence of steps for performing imprint lithography of a resist film according to another embodiment of the present invention;

FIG. 5 is a graph for illustrating the effect of the presence of a thermally insulating glass spacer layer beneath the substrate on the process windows for the heated substrate transfer step of the present invention; and

FIG. 6 is an AFM image of a stamped substrate formed according to the process sequence of FIG. 5 utilizing a glass spacer layer.

DESCRIPTION OF THE INVENTION

The present invention addresses and solves problems attendant upon the use of thermal imprint lithography, e.g., nano-imprint lithography for forming submicron-dimensioned patterns in a workpiece surface, as in servo patterning of disk-shaped substrates utilized in the manufacture of hard disk recording media. Specifically, the present invention provides a substantial and significant improvement in product throughput, energy consumption, and cost-effectiveness of thermal imprint lithography when performed as part of a continuous, automated manufacturing process, e.g., hard disk manufacture, and is based upon the discovery that the long thermal cycling intervals associated with conventional thermal imprint techniques can be eliminated, or at least substantially reduced, while maintaining full compatibility with all other aspects of conventional automated manufacturing technology for pattern formation by thermal imprint lithography for disk media fabrication.

According to a key feature of the present invention, the workpiece, i.e., substrate, including a layer of an imprintable thermoplastic material formed on a surface thereof, is pre-heated (in a separate heating means) to a pre-selected high temperature *prior* to insertion of the heated workpiece in the stamping/imprinting tool employed for performing the thermal imprint lithography, whereby the usual interval for thermal cycling of the stamping/imprinting tool between higher and lower temperatures is eliminated or at least reduced. According to another key feature of the present invention, the "process window", i.e., the maximum allowable interval between removal of the pre-heated workpiece from the separate heating means and its insertion in the stamping/imprinting tool, is increased by placement of a thermally

insulating spacer layer beneath the lower surface of the workpiece, whereby the rate of heat loss therefrom, hence rate of temperature reduction, is reduced.

FIG. 3 schematically shows, in simplified cross-sectional view, a sequence of steps for performing an illustrative, but not limitative, embodiment of a high quality, high reproduction fidelity "HTS" (Heat-Transfer-Stamp) process for performing nano-imprint lithography of a metal-based substrate/workpiece, i.e., an Al, Al alloy, or Al/NiP substrate workpiece, utilizing a conventional Ni-surfaced "master" or stamper/imprinter, which process includes the advantageous substrate/workpiece pre-heating step of the invention. Specifically, in a preliminary step, a thin film or layer of a thermoplastic polymer, e.g., polymethyl methacrylate (PMMA), is spin-coated on an annular disk-shaped Al/NiP substrate/workpiece, corresponding to substrates conventionally employed in the manufacture of hard disk magnetic recording media. In another preliminary step, a stamper/imprinter having a Ni or Ni alloy imprinting surface formed with a negative image pattern of features, e.g., a servo pattern with lateral dimensions of about 600 nm and heights of about 170 nm, is fabricated by conventional optical lithographic patterning/etching techniques, provided with a thin layer of an anti-sticking or release agent (typically a fluorinated polyether compound such as ZdolTM, available from Ausimont, Thorofare, NJ), and installed in a stamping/imprinting tool, by means of an upper mounting block in contact with the flat upper surface of the stamper/imprinter. The upper mounting block, termed a "top mold" in the figure, includes a heating means for maintaining the stamper/imprinter at an elevated temperature close to the glass transition temperature T_g of the thermoplastic polymer layer, e.g., $\sim 105^\circ\text{C}$ for PMMA. In the next step according to the invention, the substrate/workpiece is heated, as by placing the lower surface thereof in contact with a heater block separate from the stamping/imprinting tool, to an elevated temperature substantially greater than the glass transition temperature (T_g) of the PMMA thermoplastic layer, e.g., above about 105°C , typically about 200°C , after which the heated substrate/workpiece is rapidly transferred to the stamping/imprinting tool such that its lower surface is supported by a heated



bottom mold (maintained at the same temperature $\sim T_g$ as the heated top mold) and the patterned imprinting surface of the Ni-based stamper/imprinter pressed into contact with the surface of the heated thermoplastic PMMA layer of the substrate/workpiece at a suitable pressure, e.g., about 10 MPa. The short interval required for transfer of the heated substrate/workpiece to the stamping/imprinting tool for imprinting of the PMMA layer prior to lowering of the temperature of the PMMA layer below a minimum temperature required for imprinting, is termed the "process window". According to the invention, the transfer step is performed consistent with the short interval requirement of the process window, i.e., substrate/workpiece transfer is performed as rapidly as is practicable. Typically, transfer of the heated substrate/workpiece to the stamping/imprinting tool is accomplished within several seconds in order to prevent cooling of the heated PMMA thermoplastic layer to a temperature below that which provides optimal, high quality, faithful replication of the surface features of the imprinting surface of the stamper/imprinter. As a consequence of the high pressure urging of the patterned imprinting surface of the stamper/imprinter against the heated PMMA thermoplastic layer, the surface of the heated thermoplastic PMMA layer is imprinted (i.e., embossed) with the negative image of the desired pattern on the imprinting surface of the Ni-based stamper/imprinter. The stamper/imprinter is then maintained within the stamping/imprinting tool in contact with the PMMA layer and under pressure for an interval until the temperature of the substrate/workpiece with the imprinted PMMA layer thereon is lowered to the fixed temperature of the top and bottom molds, e.g., about 120 °C, after which interval the substrate/workpiece is separated from the substrate/workpiece to leave replicated features of the imprinting surface in the surface of the PMMA layer and removed from the stamping/imprinting tool.

Thus, by performing the thermal imprinting process according to a sequence of steps wherein the temperature within the stamping/imprinting tool is maintained substantially constant via external pre-heating of the substrate/workpiece to a high temperature above the glass transition temperature of the thermoplastic layer, the present invention eliminates, or at

least very substantially and significantly reduces the lengthy thermal cycling interval for heating and cooling of the stamping imprinting tool. The inventive methodology therefore affords several advantages vis-à-vis the conventional art, including, *inter alia*, reduced thermal cycling intervals; reduced imprint
 5 cycle times, e.g., on the order of from about 5 to about 100 sec., leading to greater product throughput rates; and reduced energy consumption resulting from the elimination or minimization of thermal cycling of the relatively massive stamping/imprinting tool.

Adverting to FIG. 4, schematically shown therein, in simplified cross-
 10 sectional view, is a generally similar sequence of steps for performing an alternative embodiment of a high quality, high reproduction fidelity "HTS" (Heat-Transfer-Stamp) process for performing nano-imprint lithography of a metal-based substrate/workpiece, e.g., a disk-shaped Al, Al alloy, or Al/NiP substrate for a recording medium, for forming a servo pattern therein. The
 15 process of FIG. 4 differs in key respect from that illustrated in FIG. 3 in the placement of a thermally insulating spacer layer (typically a glass layer) intermediate the lower surface of the substrate and the upper, supporting surface of the heater during the substrate pre-heating step and intermediate the lower surface of the substrate and the upper, supporting surface of the bottom
 20 mold during the stamping/imprinting step. As is evident from the graphs of FIG. 5, placement of the thermally insulating spacer layer beneath the lower surface of the substrate moderates, i.e., reduces, the rate of heat loss from the substrate/workpiece after removal of the latter from contact with the heater utilized for the pre-heating step and during the interval prior to imprinting of
 25 the thermoplastic layer. As a consequence of the lower heat loss rate provided by the spacer layer, the "process window" for transfer of the heated substrate from the pre-heating block to the bottom mold of the stamper/imprinter before T_{min} is reached is substantially increased, e.g., from about 9 sec. with no glass spacer layer to about 24 sec. with a glass spacer. The increased "process
 30 window" afforded by the glass spacer layer advantageously facilitates transfer of the heated substrates/workpieces from the pre-heating station to the stamping/imprinting tool with an additional (i.e., safety) margin before

unusable substrate/workpiece temperatures below the T_{\min} . (illustratively 140°C) are reached.

FIG. 6 is an AFM image of a servo pattern-stamped substrate formed according to the process sequence of FIG. 5 utilizing a glass spacer layer. As should be evident, the thermal imprint lithography process according to the inventive methodology is capable of providing servo pattern formats of excellent quality and replication fidelity.

Thus, the inventive methodology provides for the performance of imprint lithography with improved replication fidelity and substantially reduced cycle times, i.e., from about 5 to about 100 sec., compared with cycle times of about 15 - 25 min. according to conventional thermal imprint lithographic processing at elevated temperatures. Further, the inventive methodology readily permits the use of stampers/imprinters and substrates/workpieces of different materials, stampers/imprinters with Ni imprinting surfaces can be readily employed for imprinting of glass and metal-based substrates/workpieces, e.g., Al-based substrates, such as are conventionally utilized in the fabrication of hard disk magnetic recording media.

Moreover, the inventive methodology is not limited to use as described above in the illustrative examples; rather, the invention can be practiced with a wide variety of substrates/workpieces, such as, for example, semiconductor substrates utilized in integrated circuit (IC) device manufacture, and the imprinted patterns capable of being formed by the invention are not limited to servo patterns for magnetic recording media, and may, for example, include metallization patterns of semiconductor IC devices.

In the previous description, numerous specific details are set forth, such as specific materials, structures, reactants, processes, etc., in order to provide a better understanding of the present invention. However, the present invention can be practiced without resorting to the details specifically set forth. In other instances, well-known processing materials and techniques have not been described in detail in order not to unnecessarily obscure the present invention.

Only the preferred embodiments of the present invention and but a few examples of its versatility are shown and described in the present disclosure. It is to be understood that the present invention is capable of use in other combinations and environments and is susceptible of changes and/or
5 modifications within the scope of the inventive concept as expressed herein.

10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179
180
181
182
183
184
185
186
187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
221
222
223
224
225
226
227
228
229
230
231
232
233
234
235
236
237
238
239
240
241
242
243
244
245
246
247
248
249
250
251
252
253
254
255
256
257
258
259
260
261
262
263
264
265
266
267
268
269
270
271
272
273
274
275
276
277
278
279
280
281
282
283
284
285
286
287
288
289
290
291
292
293
294
295
296
297
298
299
300
301
302
303
304
305
306
307
308
309
310
311
312
313
314
315
316
317
318
319
320
321
322
323
324
325
326
327
328
329
330
331
332
333
334
335
336
337
338
339
340
341
342
343
344
345
346
347
348
349
350
351
352
353
354
355
356
357
358
359
360
361
362
363
364
365
366
367
368
369
370
371
372
373
374
375
376
377
378
379
380
381
382
383
384
385
386
387
388
389
390
391
392
393
394
395
396
397
398
399
400
401
402
403
404
405
406
407
408
409
410
411
412
413
414
415
416
417
418
419
420
421
422
423
424
425
426
427
428
429
430
431
432
433
434
435
436
437
438
439
440
441
442
443
444
445
446
447
448
449
450
451
452
453
454
455
456
457
458
459
460
461
462
463
464
465
466
467
468
469
470
471
472
473
474
475
476
477
478
479
480
481
482
483
484
485
486
487
488
489
490
491
492
493
494
495
496
497
498
499
500
501
502
503
504
505
506
507
508
509
510
511
512
513
514
515
516
517
518
519
520
521
522
523
524
525
526
527
528
529
530
531
532
533
534
535
536
537
538
539
540
541
542
543
544
545
546
547
548
549
550
551
552
553
554
555
556
557
558
559
560
561
562
563
564
565
566
567
568
569
570
571
572
573
574
575
576
577
578
579
580
581
582
583
584
585
586
587
588
589
590
591
592
593
594
595
596
597
598
599
600
601
602
603
604
605
606
607
608
609
610
611
612
613
614
615
616
617
618
619
620
621
622
623
624
625
626
627
628
629
630
631
632
633
634
635
636
637
638
639
640
641
642
643
644
645
646
647
648
649
650
651
652
653
654
655
656
657
658
659
660
661
662
663
664
665
666
667
668
669
670
671
672
673
674
675
676
677
678
679
680
681
682
683
684
685
686
687
688
689
690
691
692
693
694
695
696
697
698
699
700
701
702
703
704
705
706
707
708
709
710
711
712
713
714
715
716
717
718
719
720
721
722
723
724
725
726
727
728
729
730
731
732
733
734
735
736
737
738
739
740
741
742
743
744
745
746
747
748
749
750
751
752
753
754
755
756
757
758
759
760
761
762
763
764
765
766
767
768
769
770
771
772
773
774
775
776
777
778
779
780
781
782
783
784
785
786
787
788
789
790
791
792
793
794
795
796
797
798
799
800
801
802
803
804
805
806
807
808
809
810
811
812
813
814
815
816
817
818
819
820
821
822
823
824
825
826
827
828
829
830
831
832
833
834
835
836
837
838
839
840
841
842
843
844
845
846
847
848
849
850
851
852
853
854
855
856
857
858
859
860
861
862
863
864
865
866
867
868
869
870
871
872
873
874
875
876
877
878
879
880
881
882
883
884
885
886
887
888
889
890
891
892
893
894
895
896
897
898
899
900
901
902
903
904
905
906
907
908
909
910
911
912
913
914
915
916
917
918
919
920
921
922
923
924
925
926
927
928
929
930
931
932
933
934
935
936
937
938
939
940
941
942
943
944
945
946
947
948
949
950
951
952
953
954
955
956
957
958
959
960
961
962
963
964
965
966
967
968
969
970
971
972
973
974
975
976
977
978
979
980
981
982
983
984
985
986
987
988
989
990
991
992
993
994
995
996
997
998
999
1000
1001
1002
1003
1004
1005
1006
1007
1008
1009
1010
1011
1012
1013
1014
1015
1016
1017
1018
1019
1020
1021
1022
1023
1024
1025
1026
1027
1028
1029
1030
1031
1032
1033
1034
1035
1036
1037
1038
1039
1040
1041
1042
1043
1044
1045
1046
1047
1048
1049
1050
1051
1052
1053
1054
1055
1056
1057
1058
1059
1060
1061
1062
1063
1064
1065
1066
1067
1068
1069
1070
1071
1072
1073
1074
1075
1076
1077
1078
1079
1080
1081
1082
1083
1084
1085
1086
1087
1088
1089
1090
1091
1092
1093
1094
1095
1096
1097
1098
1099
1100
1101
1102
1103
1104
1105
1106
1107
1108
1109
1110
1111
1112
1113
1114
1115
1116
1117
1118
1119
1120
1121
1122
1123
1124
1125
1126
1127
1128
1129
1130
1131
1132
1133
1134
1135
1136
1137
1138
1139
1140
1141
1142
1143
1144
1145
1146
1147
1148
1149
1150
1151
1152
1153
1154
1155
1156
1157
1158
1159
1160
1161
1162
1163
1164
1165
1166
1167
1168
1169
1170
1171
1172
1173
1174
1175
1176
1177
1178
1179
1180
1181
1182
1183
1184
1185
1186
1187
1188
1189
1190
1191
1192
1193
1194
1195
1196
1197
1198
1199
1200
1201
1202
1203
1204
1205
1206
1207
1208
1209
1210
1211
1212
1213
1214
1215
1216
1217
1218
1219
1220
1221
1222
1223
1224
1225
1226
1227
1228
1229
1230
1231
1232
1233
1234
1235
1236
1237
1238
1239
1240
1241
1242
1243
1244
1245
1246
1247
1248
1249
1250
1251
1252
1253
1254
1255
1256
1257
1258
1259
1260
1261
1262
1263
1264
1265
1266
1267
1268
1269
1270
1271
1272
1273
1274
1275
1276
1277
1278
1279
1280
1281
1282
1283
1284
1285
1286
1287
1288
1289
1290
1291
1292
1293
1294
1295
1296
1297
1298
1299
1300
1301
1302
1303
1304
1305
1306
1307
1308
1309
1310
1311
1312
1313
1314
1315
1316
1317
1318
1319
1320
1321
1322
1323
1324
1325
1326
1327
1328
1329
1330
1331
1332
1333
1334
1335
1336
1337
1338
1339
1340
1341
1342
1343
1344
1345
1346
1347
1348
1349
1350
1351
1352
1353
1354
1355
1356
1357
1358
1359
1360
1361
1362
1363
1364
1365
1366
1367
1368
1369
1370
1371
1372
1373
1374
1375
1376
1377
1378
1379
1380
1381
1382
1383
1384
1385
1386
1387
1388
1389
1390
1391
1392
1393
1394
1395
1396
1397
1398
1399
1400
1401
1402
1403
1404
1405
1406
1407
1408
1409
1410
1411
1412
1413
1414
1415
1416
1417
1418
1419
1420
1421
1422
1423
1424
1425
1426
1427
1428
1429
1430
1431
1432
1433
1434
1435
1436
1437
1438
1439
1440
1441
1442
1443
1444
1445
1446
1447
1448
1449
1450
1451
1452
1453
1454
1455
1456
1457
1458
1459
1460
1461
1462
1463
1464
1465
1466
1467
1468
1469
1470
1471
1472
1473
1474
1475
1476
1477
1478
1479
1480
1481
1482
1483
1484
1485
1486
1487
1488
1489
1490
1491
1492
1493
1494
1495
1496
1497
1498
1499
1500
1501
1502
1503
1504
1505
1506
1507
1508
1509
1510
1511
1512
1513
1514
1515
1516
1517
1518
1519
1520
1521
1522
1523
1524
1525
1526
1527
1528
1529
1530
1531
1532
1533
1534
1535
1536
1537
1538
1539
1540
1541
1542
1543
1544
1545
1546
1547
1548
1549
1550
1551
1552
1553
1554
1555
1556
1557
1558
1559
1560
1561
1562
1563
1564
1565
1566
1567
1568
1569
1570
1571
1572
1573
1574
1575
1576
1577
1578
1579
1580
1581
1582
1583
1584
1585
1586
1587
1588
1589
1590
1591
1592
1593
1594
1595
1596
1597
1598
1599
1600
1601
1602
1603
1604
1605
1606
1607
1608
1609
1610
1611
1612
1613
1614
1615
1616
1617
1618
1619
1620
1621
1622
1623
1624
1625
1626
1627
1628
1629
1630
1631
1632
1633
1634
1635
1636
1637
1638
1639
1640
1641
1642
1643
1644
1645
1646
1647
1648
1649
1650
1651
1652
1653
1654
1655
1656
1657
1658
1659
1660
1661
1662
1663
1664
1665
1666
1667
1668
1669
1670
1671
1672
1673
1674
1675
1676
1677
1678
1679
1680
1681
1682
1683
1684
1685
1686
1687
1688
1689
1690
1691
1692
1693
1694
1695
1696
1697
1698
1699
1700
1701
1702
1703
1704
1705
1706
1707
1708
1709
1710
1711
1712
1713
1714
1715
1716
1717
1718
1719
1720
1721
1722
1723
1724
1725
1726
1727
1728
1729
1730
1731
1732
1733
1734
1735
1736
1737
1738
1739
1740
1741
1742
1743
1744
1745
1746
1747
1748
1749
1750
1751
1752
1753
1754
1755
1756
1757
1758
1759
1760
1761
1762
1763
1764
1765
1766
1767
1768
1769
1770
1771
1772
1773
1774
1775
1776
1777
1778
1779
1780
1781
1782
1783
1784
1785
1786
1787
1788
1789
1790
1791
1792
1793
1794
1795
1796
1797
1798
1799
1800
1801
1802
1803
1804
1805
1806
1807
1808
1809
1810
1811
1812
1813
1814
1815
1816
1817
1818
1819
1820
1821
1822
1823
1824
1825
1826
1827
1828
1829
1830
1831
1832
1833
1834
1835
1836
1837
1838
1839
1840
1841
1842
1843
1844
1845
1846
1847
1848
1849
1850
1851
1852
1853
1854
1855
1856
1857
1858
1859
1860
1861
1862
1863
1864
1865
1866
1867
1868
1869
1870
1871
1872
1873
1874
1875
1876
1877
1878
1879
1880
1881
1882
1883
1884
1885
1886
1887
1888
1889
1890
1891
1892
1893
1894
1895
1896
1897
1898
1899
1900
1901
1902
1903
1904
1905
1906
1907
1908
1909
1910
1911
1912
1913
1914
1915
1916
1917
1918
1919
1920
1921
1922
1923
1924
1925
1926
1927
1928
1929
1930
1931
1932
1933
1934
1935
1936
1937
1938
1939
1940
1941
1942
1943
1944
1945
1946
1947
1948
1949
1950
1951
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040
2041
2042
2043
2044
2045
2046
2047
2048
2049
2050
2051
2052
2053
2054
2055
2056
2057
2058
2059
2060
2061
2062
2063
2064
2065
2066
2067
2068
2069
2070
2071
2072
2073
2074
2075
2076
2077
2078
2079
2080
2081
2082
2083
2084
2085
2086
2087
2088
2089
2090
2091
2092
2093
2094
2095
2096
2097
2098
2099
2100
2101
2102
2103
2104
2105
2106
2107
2108
2109
2110
2111
2112
2113
2114
2115
2116
2117
2118
2119
2120
2121
2122
2123
2124
2125
2126
2127
2128
2129
2130
2131
2132
2133
2134
2135
2136
2137
2138
2139
2140
2141
2142
2143
2144
2145
2146
2147
2148
2149
2150
2151
2152
2153
2154
2155
2156
2157
2158
2159
2160
2161
2162
2163
2164
2165
2166
2167
2168
2169
2170
2171
2172
2173
2174
2175
2176
2177
2178
2179
2180
2181
2182
2183
2184
2185
2186
2187
2188
2189
2190
2191
2192
2193
2194
2195
2196
2197
2198
2199
2200
2201
2202
2203
2204
2205
2206
2207
2208
2209
2210
2211
2212
2213
2214
2215
2216
2217
2218
2219
2220
2221
2222
2223
2224
2225
2226
2227
222